Testing Orion's Fairing Separation System

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Abstract

Traditional fairing systems are designed to fully encapsulate and protect their payload from the harsh ascent environment including acoustic vibrations, aerodynamic forces and heating. The Orion fairing separation system performs this function and more by also sharing approximately half of the vehicle structural load during ascent. This load-share condition through launch and during jettison allows for a substantial increase in mass to orbit.

A series of component-level development tests were completed to evaluate and characterize each component within Orion's unique fairing separation system. Two full-scale separation tests were performed to verify system-level functionality and provide verification data. This paper summarizes the fairing spring, Pyramidal Separation Mechanism and forward seal system component-level development tests, system-level separation tests, and lessons learned.

Introduction

The fundamental components of the Orion Multi-Purpose Crew Vehicle fairing are similar to heritage systems as shown in Table 1. However, addition of the load share between the fairings and the Service Module requires a unique architecture and presents challenges requiring substantial testing in order to validate the design can successfully jettison loaded fairings and ensure the safety of Orion astronauts.

Table 1. Fairing System Comparison

Vehicle	Segments	Vertical Separation	Horizontal Separation	Separation Energy
Orion MPCV	Trisector	Frangible joint	Frangible joint & PSM	Mechanical springs
Ariane 5 (1)	Bisector	Thrust Rail	Frangible joint	Thrust rail
Atlas V 400 (2)	Bisector	Pyro Sep Bolts	V-Clamp	Spring thrusters
Atlas V 500(2)	Bisector	Thrust rail	Sep bolt	Thrust rail
Delta IV (3)	Bisector	Thrust rail	Sep bolt	Thrust rail
Delta IV Heavy(3)	Trisector	Thrust rail	Sep bolt	Thrust rail
Pegasus (4)	Bisector	Sep bolt / clamp band	Frangible joint	Gas thrusters
Saturn V/Skylab (5)	Quad	Thrust rail	Latchpins	Thrust rail

Extensive development and qualification testing was and is currently being performed on each of the fairing components. This paper focuses on the early development testing for the fairing Pyramidal Separation Mechanism, spring assembly, and forward seal as well as results from the more recent system-level fairing separation testing.

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Orion Fairing Design Overview

The Orion fairing system, referred to as the Spacecraft Adapter Jettisoned Panels shown in Figure 1, provides protection for the Service Module (SM) on the pad and during ascent as well as carries approximately half of the vehicle structural loads up through jettison. During the Orion Exploration Flight Test -1 (EFT-1) mission, the fairings are jettisoned under approximately 0.2g of thrust at an altitude of approximately 1830 m (600,394 ft).

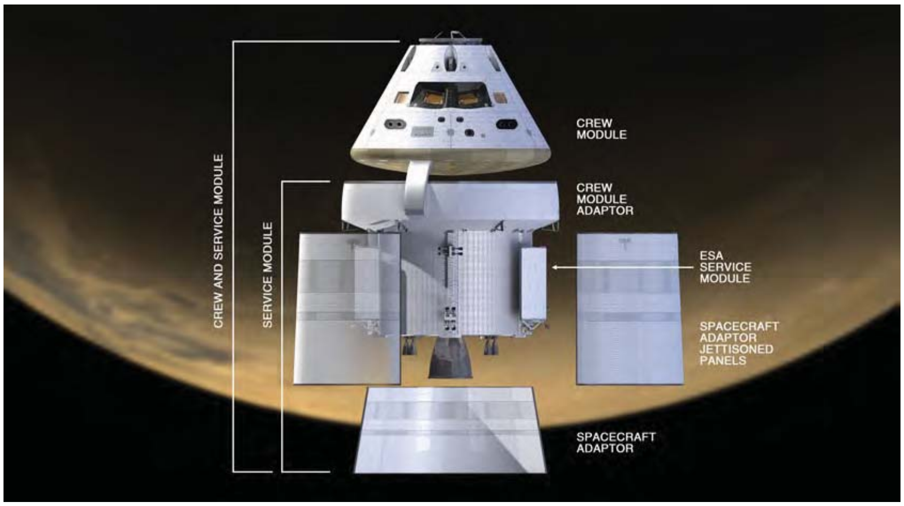

Figure 1. Orion Configuration (Image Courtesy: NASA)

The fairing jettison system shown in Figure 2 is comprised of composite tri-sector segments which are severed by frangible joints and pyrotechnic separation bolts, then jettisoned with springs and hinges. The frangible joints are the primary load path between each of the fairing panels along the horizontal and vertical seams. Each frangible joint contains a single core charge initiated by Explosive Transfer Line at opposite ends for redundancy.

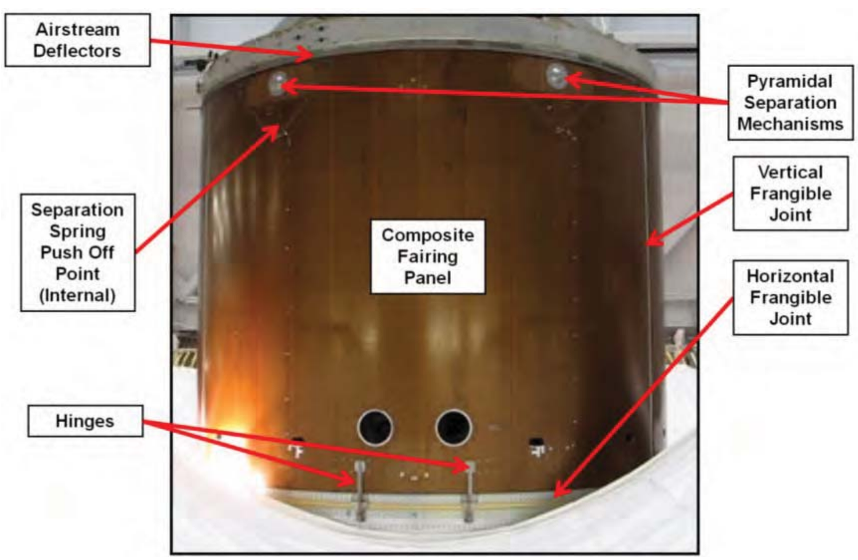

Figure 2. Fairing Components

After severance of the frangible joints, each panel is released by two redundantly actuated pyrotechnic separation bolts between cup-cone interfaces called Pyramidal Separation Mechanisms (PSMs). The PSM transfers load from the inner load path (SM) to the outer load path (fairing panels) and allows

clearance of these load bearing surfaces during deployment. Made from titanium with CANADIZE® coating, the PSM incorporates variable angle surfaces with shallow angles taking shear loads and steeper angles providing clearance. Selection of the primary load bearing angle involved a careful balance of minimizing axial force induced into the pyrotechnic separation bolt and frictional resistance during separation.

Once the PSMs are released, the fairings are pushed away with titanium spring actuators which rotate the panels about hinges along the lower separation plane. The Push-Off Springs are located near the top of the panels adjacent to the PSM and provide initial deployment force for the fairing panels. There are two springs per panel sized to provide positive margin in the event of a spring coil fracture per NASA human rating requirements.

The forward seal system is a circumferential seal comprised of an elastomeric p-shaped seal compressed by titanium flexures called airstream deflectors. Together they create an environmental seal between the top of the fairing panels and prevent air ingestion during ascent while allowing for relative deflections between the sealing surfaces. The seal system also acts as a conductive path between the avionics ring and the fairing panels.

Component Testing

Component-level development testing evaluated the individual components of the system and provided valuable information allowing for mass and performance optimizations. Load testing was performed on the Pyramidal Separation Mechanisms to ensure the material and coatings could endure the high loads and cyclic wear during ascent and still separate. Spring testing was performed to validate design margins and evaluate performance under the stressing ascent vibration environment. The seal system was cycled in order to validate life requirements. Each of these tests provided insight into the performance of each component against its most stressing environment and in most cases required some modification to ensure all performance requirements would be met during qualification.

<u>Pyramidal Separation Mechanism Testing</u>

Tests were conducted to evaluate the performance of the cup-cone design to bear load and the effectiveness of the lubricant. Figure 3 shows a cross section of the flight design.

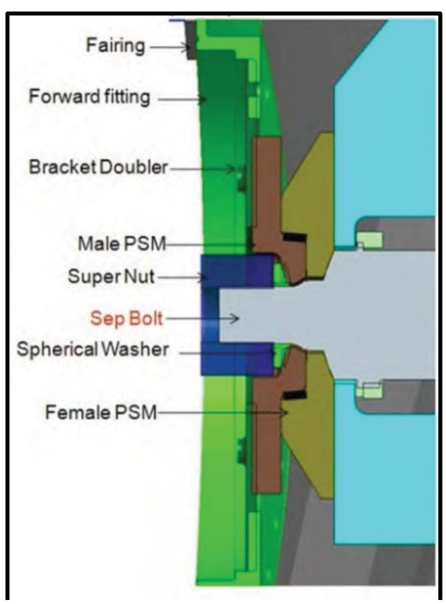

Figure 3. PSM Cross Section

There were three rounds of initial PSM development testing that focused on validation of the ramp angles, material and coating performance. The first test identified refinement of the load bearing surfaces and manufacturing tolerances. The second test validated the refinements and changes learned from initial testing and to predict slippage in the joint. The third test was used to verify that the material and coatings would survive the load and life requirements.

Test fixtures were designed to support the PSM halves and mount to a servo-hydraulic load frame. The fixture geometry was designed such that the prescribed ascent loads and moments could be achieved via a single load-axis. Two fixture sets were machined, one for a maximum axial case and the other for a maximum lateral case. Modifications were made to these basic designs to include both forces and moments when the predicted loads changed. In all, the test setup included 10 Linear Displacement Transducers (LDT), an instrumented Strainsert bolt (first and second test), four strain gages mounted on an inert flight-like bolt (third test), a main load cell to control the applied load levels, and an LDT to monitor overall applied displacements.

The first test revealed the critical load bearing surfaces were not engaging properly. In order to correct this, shims were fabricated of variable thicknesses and placed between the two nodes to determine the proper gap. Changes were also made to the interfacing radii for each of the nodes and to the primary critical load bearing surfaces to minimize contact stress between the two halves. The second test conducted validated the changes made to the design. Slippage was more predictable with smoother hysteresis deflection curves. While the test showed heavy burnishing there was no galling and the parts easily separated. Figure 4 shows the wear differences between the first and second test configurations.

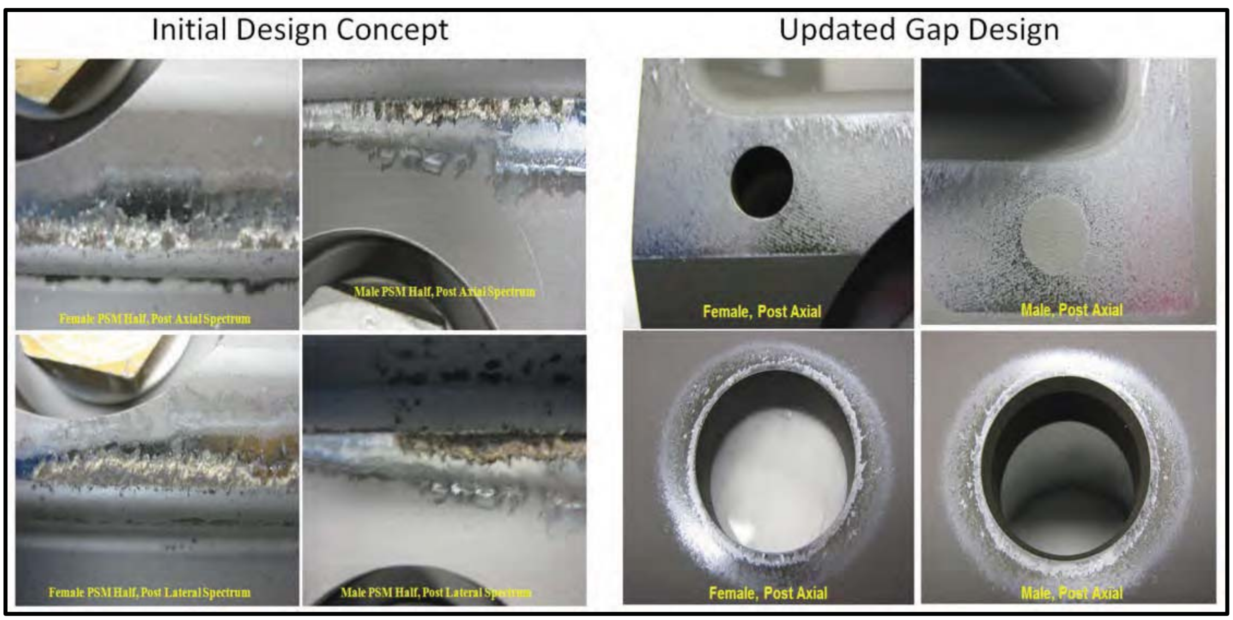

Figure 4. Wear Characteristics of Initial and Updated Design Concepts

The third test series used a flight-like inert separation bolt which was instrumented with four uniaxial strain gages as well as a new test fixture. This test evaluated the preload operation and measured the resultant axial and moment loads in the separation bolt over the increased life cycle count based on updated analysis. The cycle count increase was based primarily on updated ground cycle analysis which was typically low load, but had to be accounted for. Data from this round of testing (shown in Figure 5) was also used to determine load when the PSM slipped. This final test confirmed the design was robust enough to survive the loads at twice the number of life cycles and no further modifications were required.

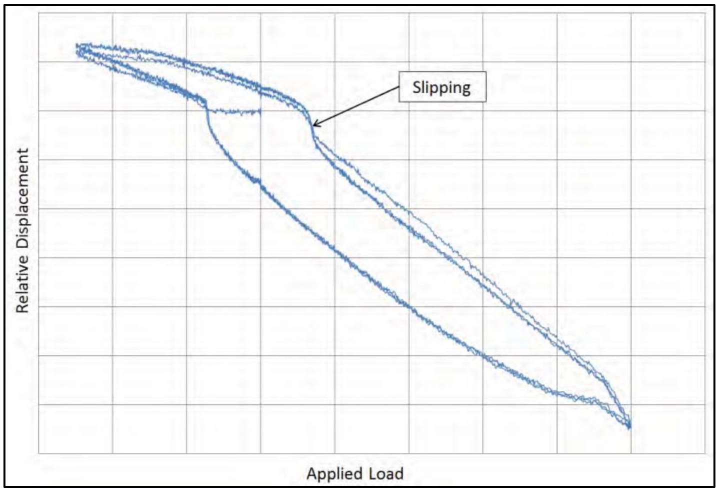

Figure 5. PSM Load versus Displacement

Spring Assembly Testing

A "Test Like You Fly" approach was followed for spring testing with initial wear-in/run-in followed by random vibration then multiple functional tests to verify design margin. Figure 6 shows the general cross section of the spring assembly and its various components.

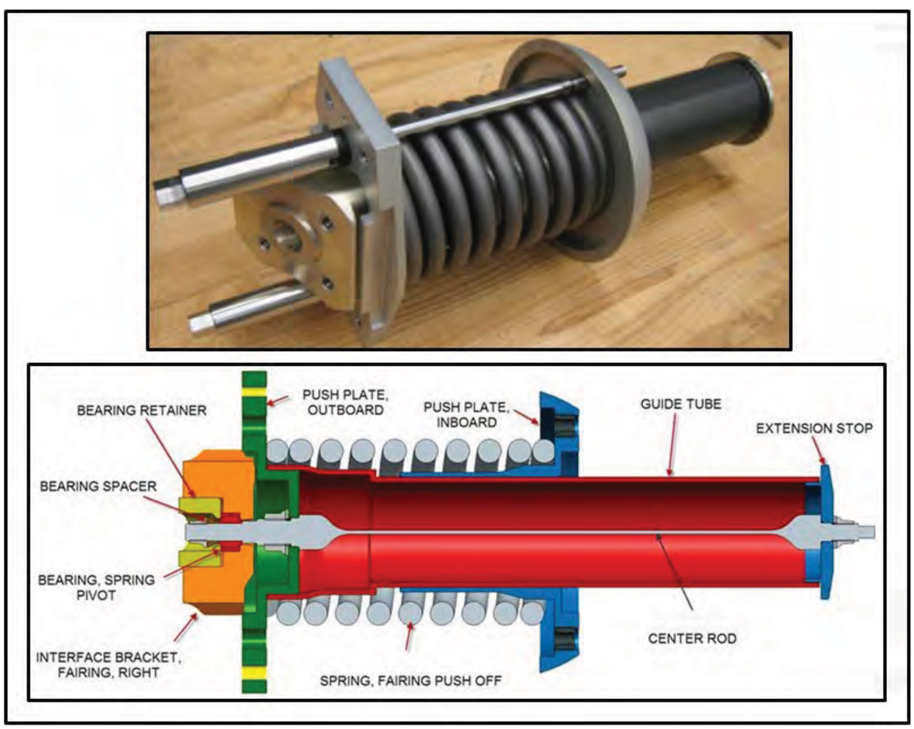

Figure 6. Fairing Spring Assembly

Initial wear-in/run-in was performed to burnish close running fit areas and evaluate potential friction losses within the assembly by measuring the force versus displacement over the working height of the spring. Test data showed minimal losses (1% or less) compared to the individual spring coil testing performed by the vendor.

Random vibration test levels initially started out as benign but as dynamic modeling matured the levels more than doubled. This gave cause for concern of excessive loading of the spherical bearing within the assembly which allows for proper spring alignment during deployment. Under random vibration testing, the spring surged in a smooth sinusoidal motion along the coil axis for the most part but at certain levels the peak displacements were significantly amplified and chaotic. This motion induced higher than expected loads into the spherical bearing.

Another noteworthy event was the amount of off-axis displacement resulting in cyclic impacting of the coil with its adjacent assembly hardware. At qualification levels the titanium spring damaged the TUFRAM®-coated aluminum parts and generated debris which was deemed unacceptable. Three options were selected and tested; bare aluminum, aluminum with hard anodize coating, and 304 CRES stainless steel. Ultimately, the soft 304 CRES stainless steel performed the best by absorbing the impact energy. Post-test results had the appearance of peening but without the effect of creating debris. Figure 7 shows post vibration test results of the original anodized aluminum and the final 304 CRES design.

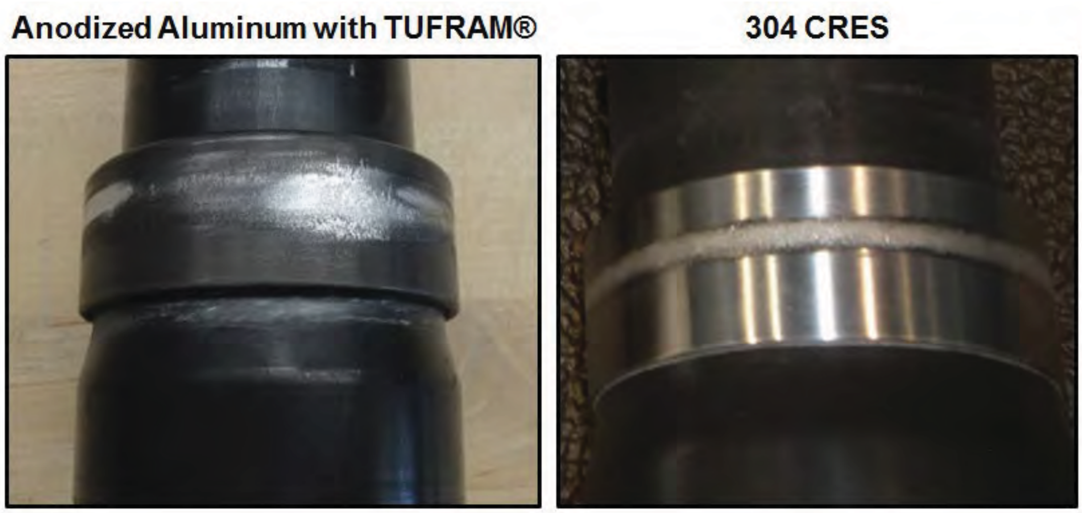

Figure 7. Anodized Aluminum and 304 CRES Vibration Test Results

Another issue noted was ground bonding paths. The use of a spherical bearing and a dry film lubricant in the race did not allow for a clean path resulting in intermittent grounding.

Functional testing was conducted after vibration testing to be more flight like with regard to environment exposure. The functional test verified energy margins and hard stop functionality. No issues were found during functional testing. In fact, the functional test fixture was modified to accommodate lanyard connector testing using the same development springs. Overall, the development springs have become a great test asset with some being functioned as many as 15 times with no detrimental damage or wear.

Forward Seal Testing

The forward seal system shown in Figure 8 is comprised of two components; a specially designed three segmented elastomeric seal and titanium aero deflectors.

Figure 8. Forward Seal System

The aero deflector is essentially a flexure capable of protecting the elastomeric seal from the harsh ascent thermal environment while compressing it against the sealing surface and providing a ground path. The shape of the aero deflector was complex due mainly to the large design deflections (up to 1.3 cm (0.5 in) between sealing surfaces) and required a combination of conventional machining and wire Electrical Discharge Machining (EDM) to maintain the tight manufacturing tolerances. The original avionics ring surface tested was aluminum with electroless nickel which provided a smooth finish with high hardness and excellent wear resistance without any lubricant. However, application of the electroless nickel to the large avionics ring surface was found to be prohibitive due to cost and schedule constraints. Brushed-on nickel coating was eventually chosen. Figure 9 shows the wear on the base material after 2000 cycles of both electroless nickel and brushed-on nickel coatings with no lubricant. From these initial tests it was determined that the addition of lubricant was required if brushed-on nickel plating was to be used.

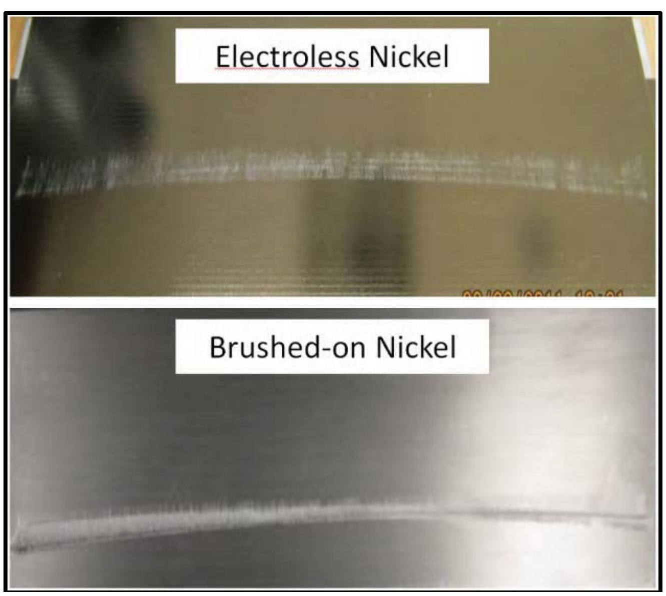

Figure 9. Nickel Coating Wear after 2000 Cycles

Numerous tests followed trying to find a lubricant that would provide the necessary wear resistance with the brushed-on nickel.

Eventually, the trade study was narrowed to five lubricants; Nye Lubricants Inc. special formula paste, Braycote® 602EF, Krytox®, Rheolube™ 2004, and Rheolube™ 2004 with MOS_2. The first test conducted was an oven test to evaluate the resistance to controlled heat of 66 °C (150 °F) for a short duration (to simulate ascent heating). While several of the lubricants shown in Figure 10 did not remain in place, there is some concern that the test was not representative of flight.

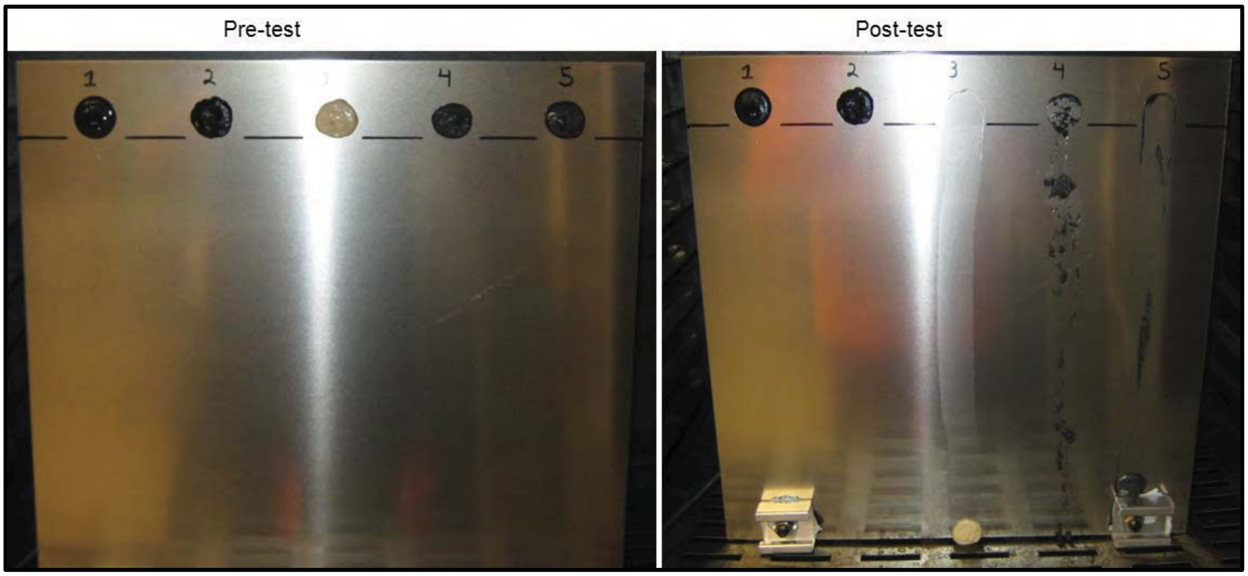

Figure 10: Controlled Oven Test

Each of the five lubricants are currently planned to undergo a 30-day environmental exposure test at the Kennedy Space Center. In addition, a final round of wear testing will be performed. After these tests are complete, the final lubricant selection will be made.

System Testing

Overview

Due to the dynamic nature of fairing jettison induced by the load share event as well as the complex interaction between mechanisms, a system-level test was performed to verify each of the components worked together under flight-like separation conditions. The series of tests designed to verify performance and gather data for the analytical model included test fixture characterization, panel-level testing and full-scale separation tests. Multiple separation tests were required to understand the sensitivity of the system to load and thermal conditions.

Test Fixture

In order to achieve flight-like boundary conditions, dynamic response and load share, a special test fixture was designed to simulate the Service Module. The fixture incorporated adjustable features allowing the overall structure to be simplified for manufacturability and cost while ensuring proper axial stiffness and dynamic response. The primary stiffness tuning feature was a simple spring plate located at each of the six load path interfaces. The second method for tuning of the structure was adjustability of the load head interface.

Structural stiffness and modal testing of the fixture was performed to help with tuning of the stiffness, adjusting load share, and anchoring the analytical model. Stiffness testing included thirteen load cases to evaluate the axial stiffness of the fixture and PSM interface. Instrumentation of the structure included 156

strain gage channels, 28 displacement measurements and 6 load cells in addition to input load and displacement. Most loads were input using hydraulic actuators tied down to the floor or the reaction frames. Figure 11 shows the test fixture including a frame used to mount instrumentation.

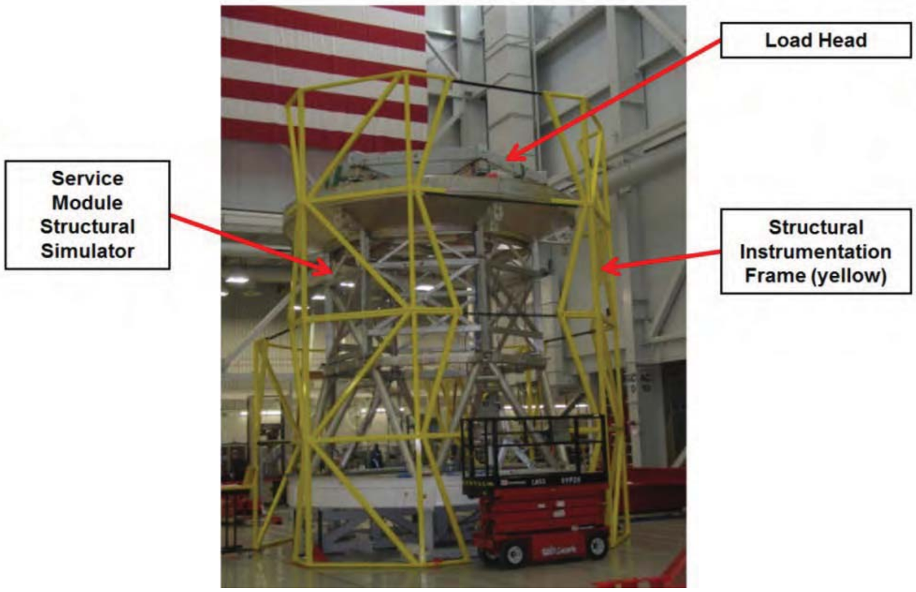

Figure 11. Test Fixture Stiffness Testing

Moment loads were applied using pulleys and offloading weights in order to simplify operations. Each load case was applied three times while displacement, load and strain gage data was recorded. The displacement and strain data was used to independently evaluate the stiffness and predict load share. While strain and displacement results were within 3% of each other, the overall initial stiffness prediction was off by ~25%. It was found that interactions between interfaces at the load head and spring plate were more complex than initially modeled. Capturing these differences in the finite element model was crucial in correlating test data to model predictions. Ultimately, results were still within the tuning capability of the fixture and no design changes were required.

After initial axial tuning, local bending and torsion load cases applied to the PSM interface provided additional information which led to further refinement of the stiffness and load input interface. The adjustable features of the fixture were used to obtain loading of both the inner structure and the fairings within acceptable design parameters. In order reduce schedule, the final load share was adjusted to within 10% of the predicted value with load biased higher to the fairings to ensure a conservative test.

After tuning of the stiffness, modal testing of the fixture was performed to capture flexible body modes in axial, bending and torsion with 129 degrees of freedom over 65 grid points. Ten target modes were initially identified over the frequency range of interest (0-50 Hz) and eleven were excited during testing. Results were then used to refine the finite element model. Similar to a fixture evaluation for vibration or acoustic testing, fixture stiffness characterization is recommended for dynamic separation tests which rely on proper boundary conditions and loads. Even with advances in finite element modeling, complex boundary conditions can be difficult to predict without some level of testing. Adjustability within the Orion fairing test fixture accounted for uncertainties in the predicted stiffness while allowing for simplification of the overall structure to reduce cost and fabrication schedule. In addition, the characterization provided insight into potential model uncertainties with the flight structure and provided valuable information for correlating the test fixture model. Characterization of the flight Service Module is currently scheduled for early 2014.

Separation Test Results

The first separation test was considered successful even though only two of the three panels fully deployed as seen in Figure 12. The two panels that did fully deploy included the most highly instrumented panel (left side of figure) which provided the necessary data for model correlation and risk reduction.

Figure 12. Separation Test #1 (Image Courtesy: NASA)

The third panel did not fully deploy due to an unexpected asymmetric interference which had not been accounted for in the dynamic separation model.

The nearly 300 channels of instrumentation during the separation test provided sufficient data to gain a better understanding of how the various factors such as gravity, air resistance and friction affect the dynamic behavior of the panels as they deploy. Test results also showed dynamic interaction between the panels was less than predicted and that the single separation event was similar to three independent tests. This was highly beneficial since only two panels deployed. Figure 13 shows the model predictions of the panel deployment before the test and after correlating the model to the data.

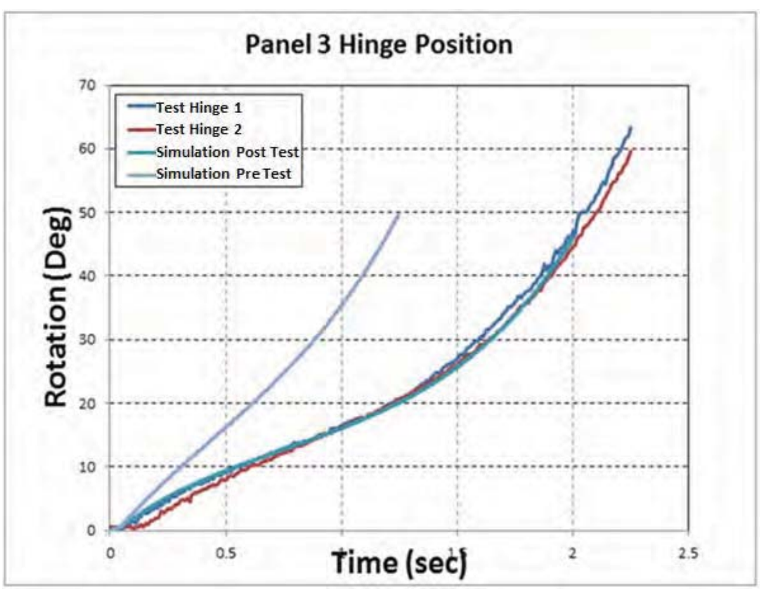

Figure 13. Fairing Position versus Time

After the first separation test, a panel free-fall test was performed on the panel that failed to separate. This test was developed to gather data to reduce uncertainties in the rigid body motion and losses due to air effects and friction. For this test, a single panel was pulled slowly over its center of gravity using an actuator and pulley system. The aero model of a flat plate worked surprisingly well in predicting aero effects during ground testing, however, the aero effects were only a small portion of the total factors that effected the fairing deployment response. It should be noted that while the deployment failure was unexpected, the free-fall test had been previously planned and the un-deployed panel position greatly simplified the logistics and implementation of this test.

The second separation test was performed with one panel heated to 93 °C (200 °F) to simulate flight environments as shown in Figure 14. Panel heating was predicted to increase loads, induce panel warping and amplify the dynamic response of the fairing during separation. Only one panel was heated to save cost and schedule associated with a more complex heating system. Multiple checkout tests of the heater system were performed prior to separation and data was collected for each checkout to gather additional data for model correlation including effects on load share.

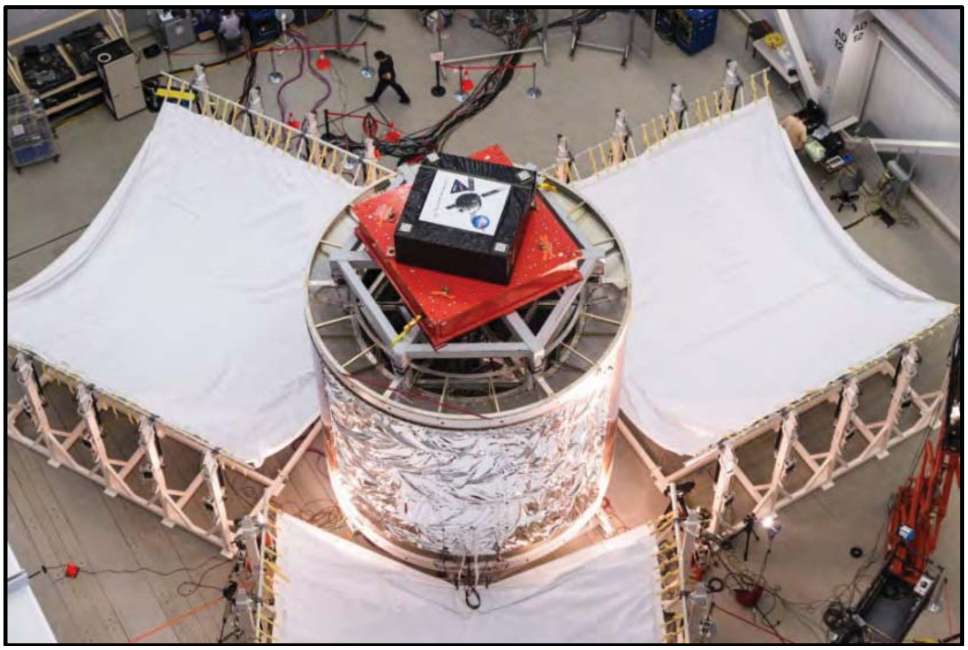

Figure 14. Separation Test #2 Heated Panel

All three panels successfully jettisoned during the second test (Figure 15). The geometry modification, margins and clearances were validated and it was found that thermal effects were slightly less than predicted.

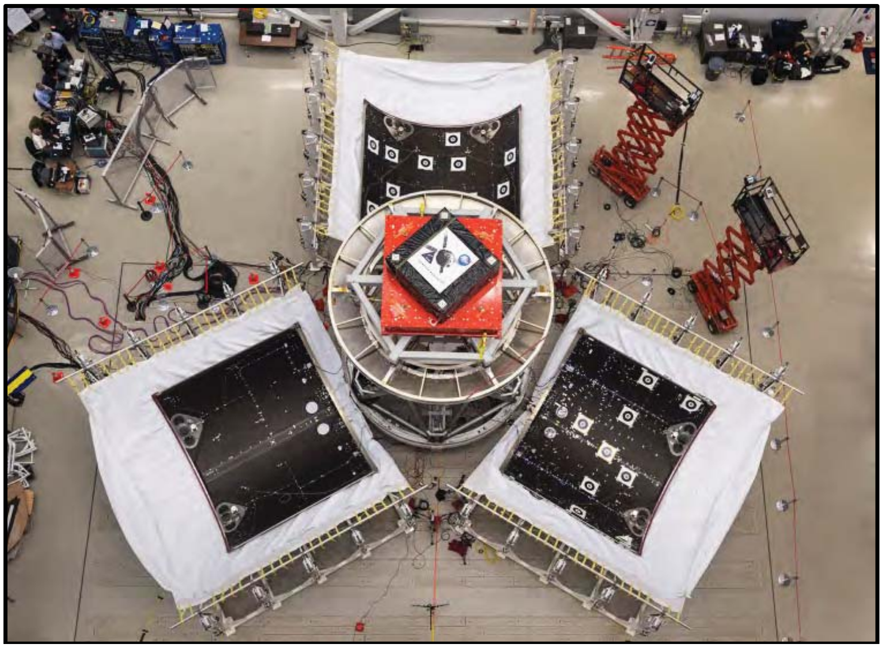

Figure 15. Separation Test #2 Jettisoned Panels

Lessons Learned

As with most test programs general lessons learned such as "test early" and "test like you fly" were continually being weighed against design finalization, cost and schedule constraints. However, some specific lessons were learned during the Orion fairing tests. The following is a list of those lessons learned along with some further information and recommendations.

- Titanium with CANADIZE® coating with a molydisulfide dry lubricant provided adequate galling resistance for the PSM cup/cone separation interface; however, other materials may have been more efficient as loads and resulting contact stresses increased. Minimizing gaps and overall relative motion reduces wear.

- Coatings and lubricants are very difficult to predict how they will respond to different environments. Testing is critical to understand them and to demonstrate that the selected system will survive both the load levels and the required life span. Part of the selection process and testing should consider what the consequence will be if/when the lubricant fails. Lubricant compatibility with surrounding materials is also a concern. During testing of the aero deflectors, one lubricant tested did not survive; it was discovered later that the lubricant had reactivity issues with both of the interfacing materials. Additionally surface finishes of substrates that receive coatings is critical.

- Titanium is not an ideal material in random vibration environments; it has very little structural damping which often results in very high amplification of vibration inputs. This was evident during the testing of both the spring and the hinge (not discussed in paper). In both cases, the response due to a random vibe input was significantly higher than expected and in the case of the spring resulted in several issues that had to be resolved.

- Coil springs can exhibit unanticipated response in vibration environments. During random vibration testing of the spring, it was found that the response was highly nonlinear (motion was excited in all directions, not just the input direction). Additionally, the amount of motion seen in the spring was much greater than anticipated, which resulted in the spring contacting the inner guide tube. The spring motion also resulted in a load amplification effect along the spring axis (surging).

- Perform characterization testing for fixtures supporting dynamic events. It is standard practice to perform a bare fixture evaluation for vibration and acoustic testing. This philosophy may also be applied to dynamic separation tests. If the test fixture can have an impact on the dynamic behavior of the test article, it may be necessary to perform some level of characterization testing on the fixture itself. This can include static load, modal or simple functional testing with a known rigid test article. This testing could eliminate analytical uncertainties even with seemingly 'simple' structure. The fixture testing performed for the fairing separation test provided data for adjustments to the analytical model.

- Make sure all design aspects are accounted for in the dynamic simulation of the separation event. When a Finite Element Model is developed for dynamic separation analysis, ensure all proper critical clearance elements are transferred from the CAD. There was a small piece of hardware that snagged on the test fixture in the first separation test and resulted in one of the fairings not separating. Had this part been included in the model, the issue would have been identified and corrected prior to the test.

Conclusion

Each test has provided critical data necessary for analytical model validation and better understanding of the components and the system. PSM wear testing pushed the limits of the CANADIZE® coating which required changes to the geometry. Ultimately, the contact stresses were reduced and the design was able to meet the life requirements under load and provide adequate clearance for separation. Spring testing showed how the vibroacoustic environment was the primary design driver. The softer CRES material was ultimately chosen to mitigate wear and debris generation. Deflector testing validated the flexure design over the relative large deflections required. While the electroless nickel was shown to be far superior for this application, the cost and schedule constraints required an alternative solution. Ultimately, the brushed-on nickel met all design requirements once the proper lubrication was found. System-level fairing separation testing showed how a small geometric interference and reduced ground margins can provide unexpected results. While flight margins are significantly higher, the design changes made increased critical clearances to eliminate any potential recontact during ground or flight jettison. The second separation test was a complete success and all margins and clearances were validated.

Tests discussed here are only a subset of those required to fully verify all requirements necessary for human rating of the Orion fairing system. Additional tests include other component development testing as well as qualification testing being performed in support of the EFT-1 mission. The final test will include a full-scale system-level separation test with flight hardware which is required for human rating the fairing separation system and the Orion vehicle.

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